Enabling the On-line Intrinsic Evolution of Analog Controllers

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Background

- The Authors have worked previously on Analog Controllers. Published in July 2003:
  - *Intrinsic Hardware Evolution for the Design and Reconfiguration of Analog Speed Controllers for a DC Motor*, 2003 NASA/DoD Conf. On Evolvable Hardware, Chicago, IL, July 2003.
  - *Hardware Evolution of Analog Speed Controllers for a DC Motor*, E. Cantu-Paz, et. al., (Eds.), GECCO 2003, LNCS 2723, July 2003, pp. 442-453.
- Used JPL developed Stand Alone Board Level Evolvable (SABLE) System as platform for controller evolution
- SABLE is a hardware platform incorporating the JPL designed Second Generation Field Programmable Transistor Array (FPTA2)
- DC servomotor and driver electronics are the controlled plant

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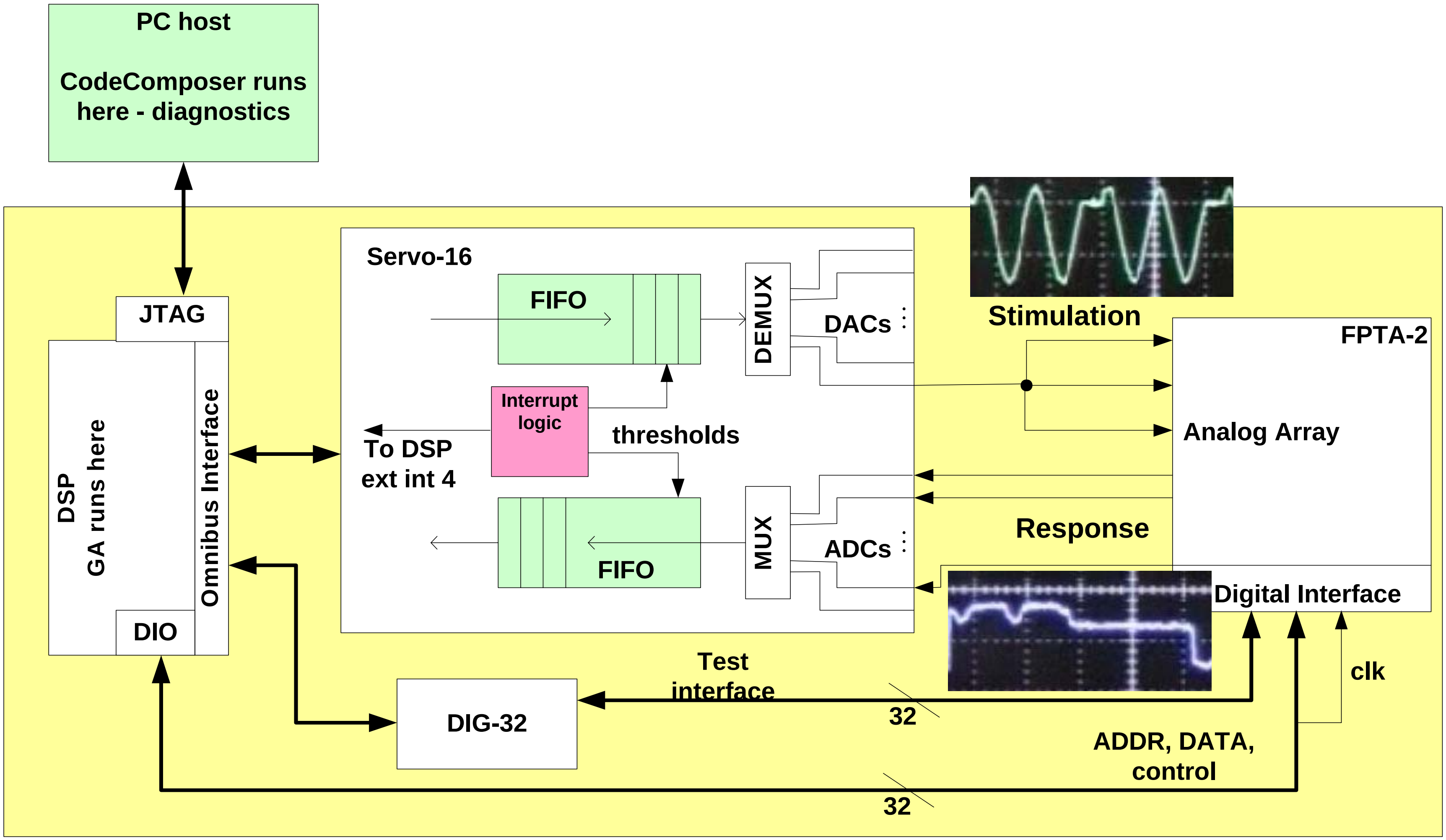
JPL SABLE System



Evolvable Controller Configuration

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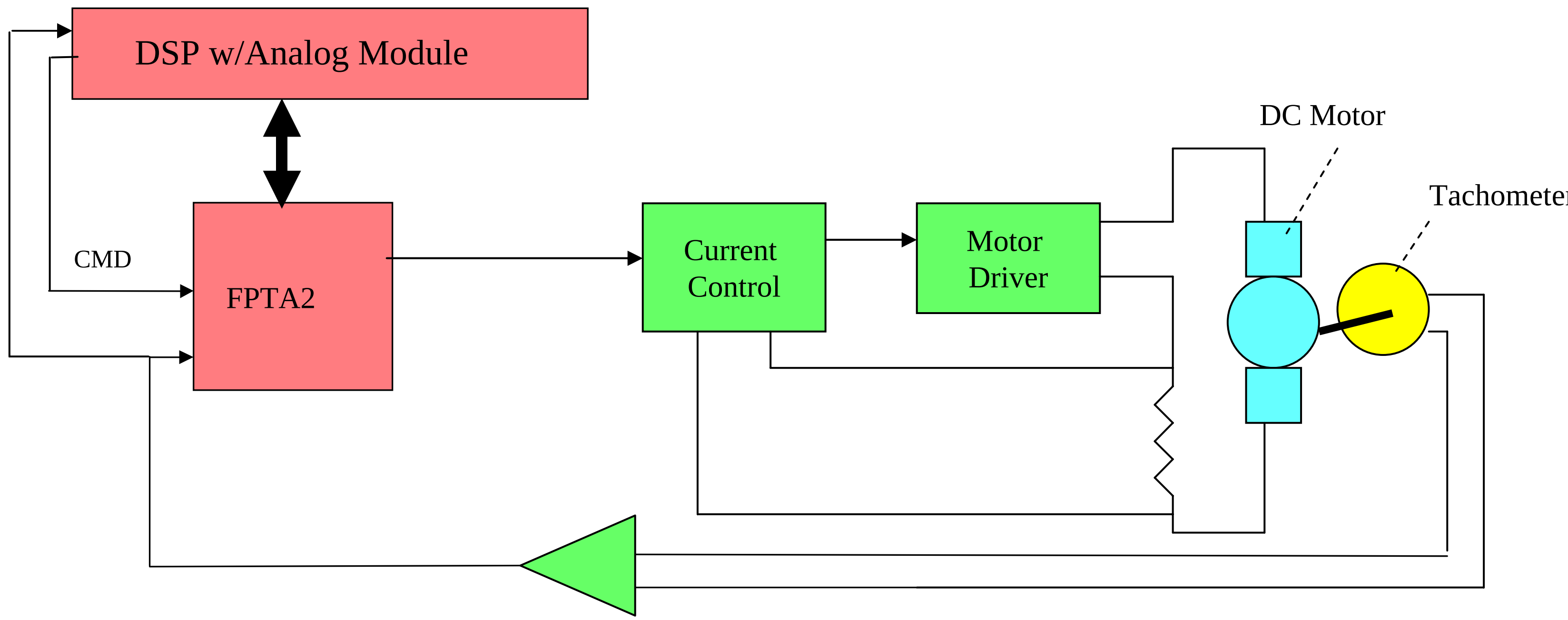

Error = CMD - Feedback

Diagram of the experimental configuration for hardware evolution of analog motor speed controllers

Evolvable Controller Configuration

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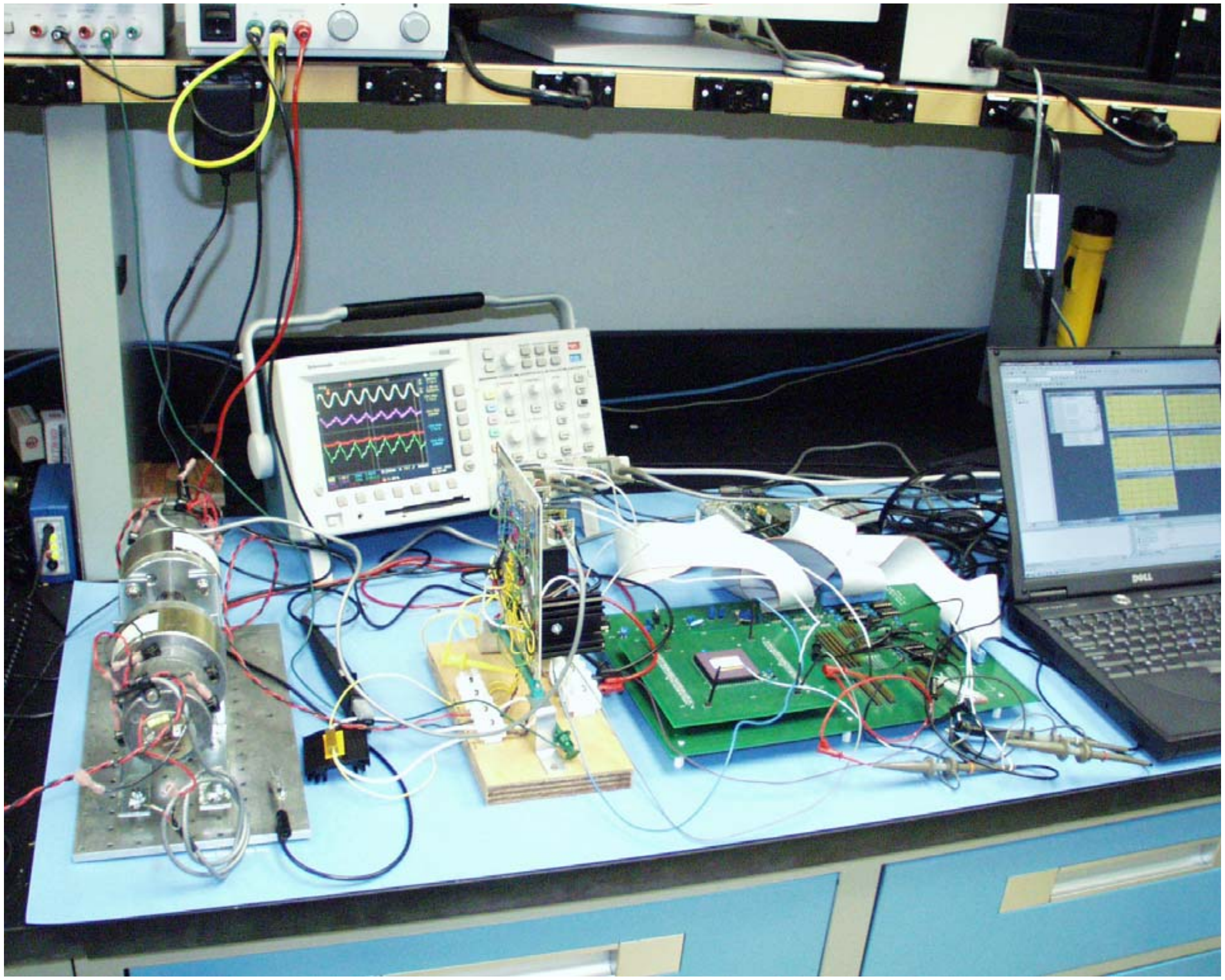

Hardware configuration for evolution of an analog motor speed controllers

Performance of the Evolved Controller

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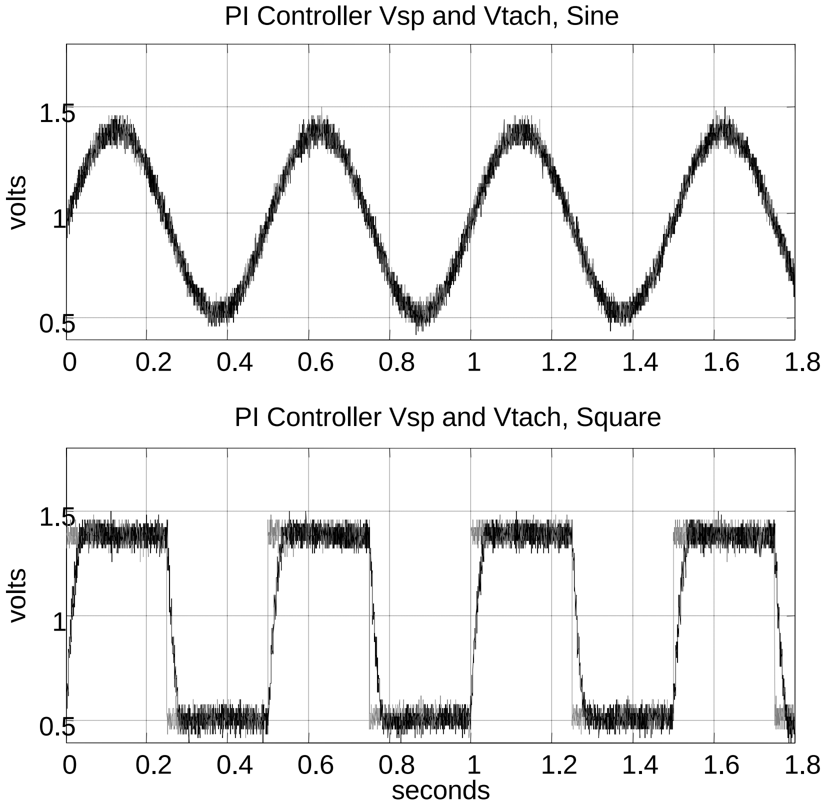
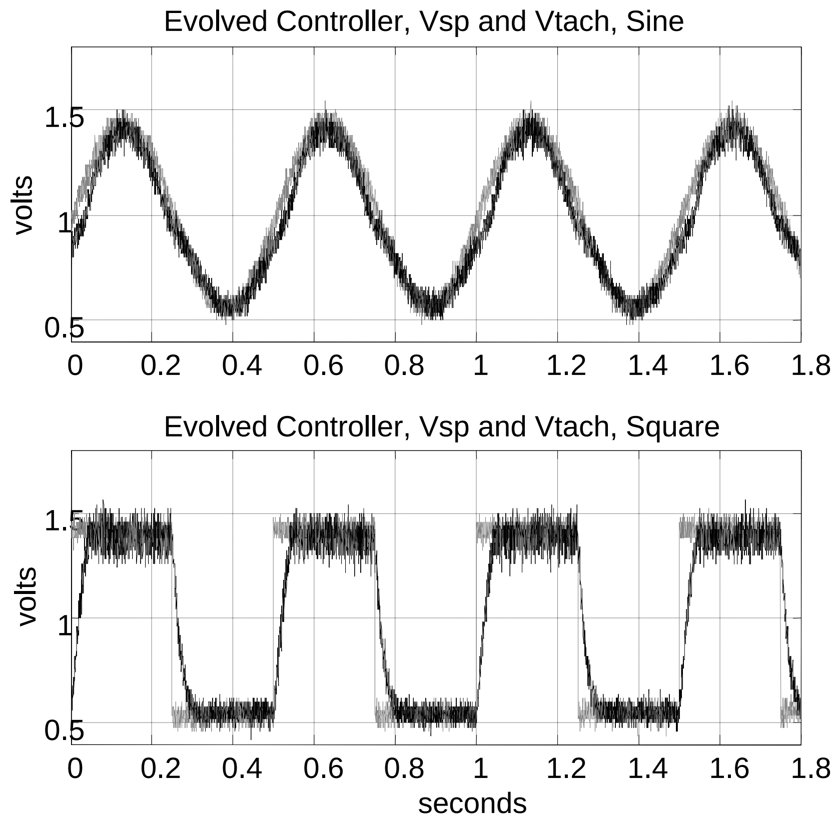


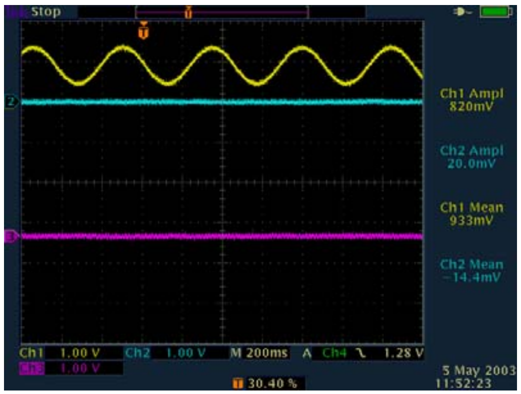
Motor speed response obtained using conventional PI controller.
Vsp is gray, Vtach is black

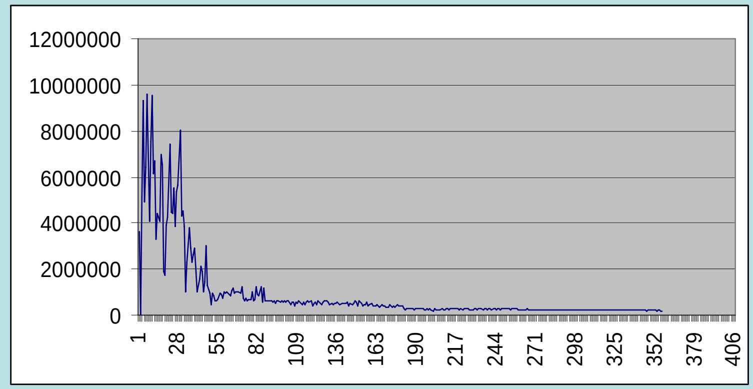


Motor speed response obtained using an evolved controller.
Vsp is gray, Vtach is black

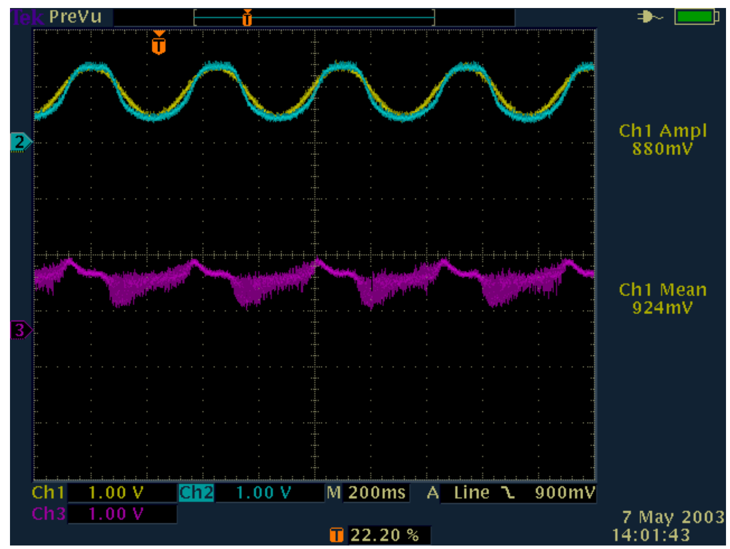
Reconfiguration for Fault Tolerance

Performance recovery with switches 71, 19 and 24 forced open to simulate faults.





Fitness vs. Generation



Opening these three switches represents severe damage:

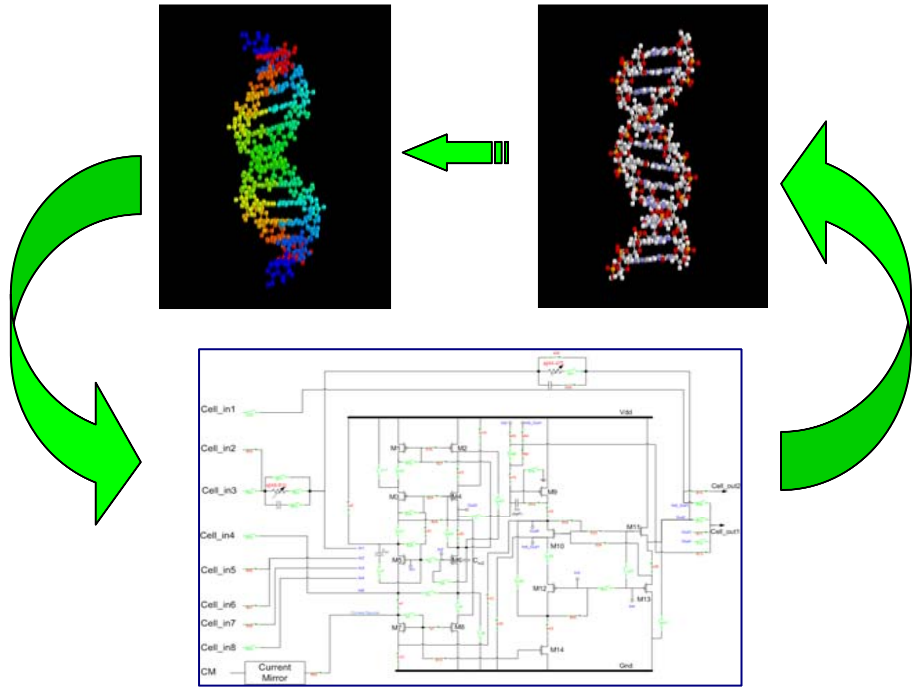
S71 & S19 cause output to flat line

S24 causes output switch between limits

Recovered response after 356 generations

Evolvable Analog Controllers

- Objective
  - Analog Controllers that autonomously
    - Configure structurally and tune internal parameters
    - Reconfigure to accommodate unexpected changes in the controlled plant
    - Self heal to tolerate internal faults



- A side effect of the evolutionary process is that during evolution there are necessarily poor configurations to be evaluated which could cause damage to the plant.
- This work concerns the development and implementation of a safe, intrinsic Evolvable Analog Controller (EAC) architecture able to evolve controllers on-line in the presence of these poor configurations.

Evolvable Analog Controllers

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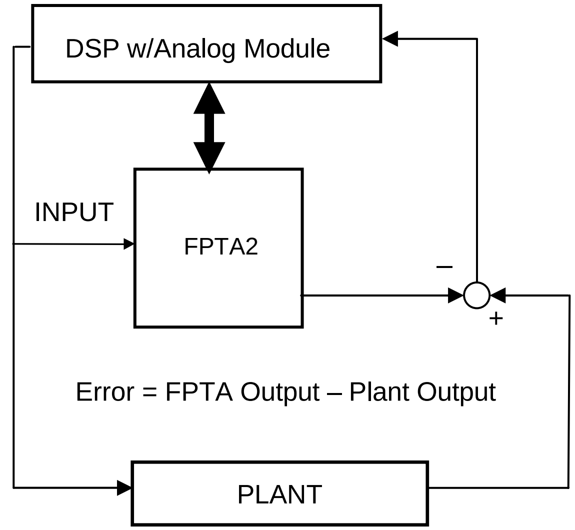
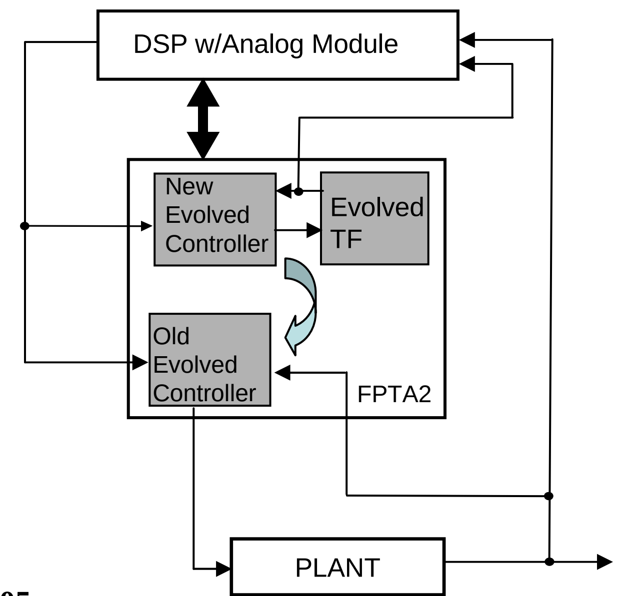
- Controller structure includes
  - automatic generation of hardware models (transfer functions) for evaluation of evolved controllers before applying them to the real plant.
  - Evolution of controllers evaluated against the evolved hardware transfer functions
  - Connection of acceptable evolved controller by
    - Relocation in reconfigurable device to connect it to the plant

    OR

    - Using analog switches external to the reconfigurable device





Initial Plant for Proof of Concept

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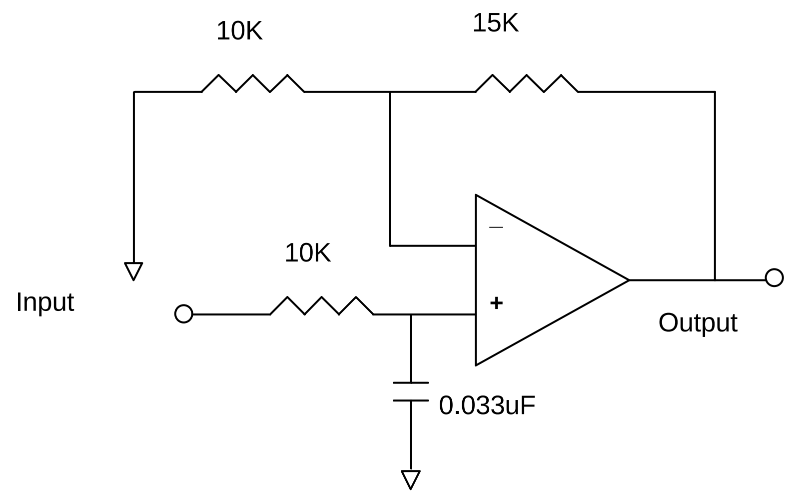
- Simulated analog plant (op-amp based) used to develop approach for evolution of hardware models
- Experiments showed the FPTA performs better in evolution of transfer functions for systems with frequencies from 10 Hz to 10K Hz
- Servomotor system has bandwidth of <<10 Hz



$$\frac{Vo}{Vi} = \frac{7575}{s + 3030}$$

Simulated analog plant and transfer function. Bandwidth is 482 Hz with s.s. gain 2.5

Dynamics similar to that found in a low-Inertia, high-speed servo system, such as a disk drive.

Evolving Transfer Functions

- Why evolve transfer functions in hardware?
  - Analog simulations of physical systems can more accurately match the continuous time performance, especially in high speed systems.
  - Hardware simulations are real-time simulations
  - Evolving analog transfer functions provides the freedom to combine electronic components in any configuration necessary.
    - May provide tolerance to faults induced by extreme environments and age
    - May aid in the identification of non-linear transfer functions caused by the presence of faults in the plant.

Evolving Transfer Functions

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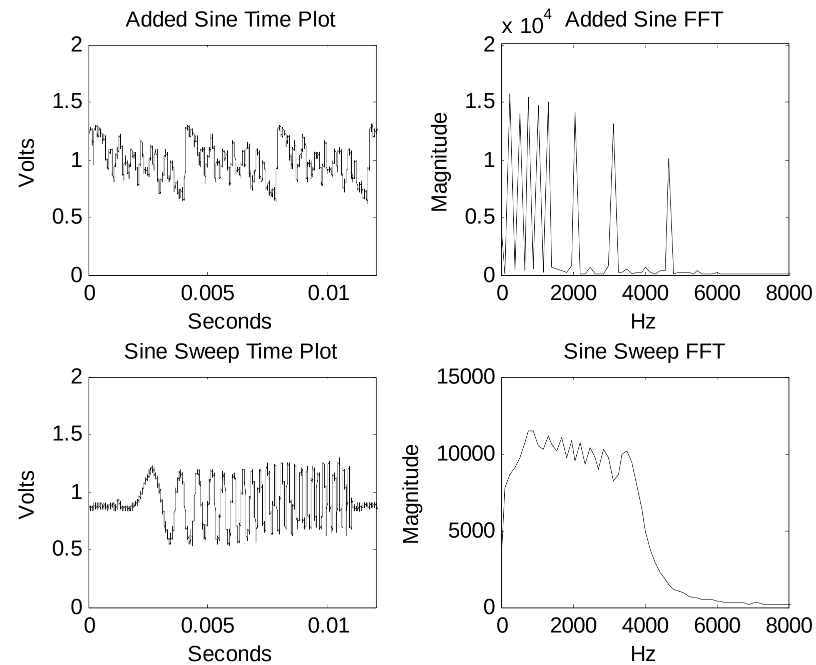
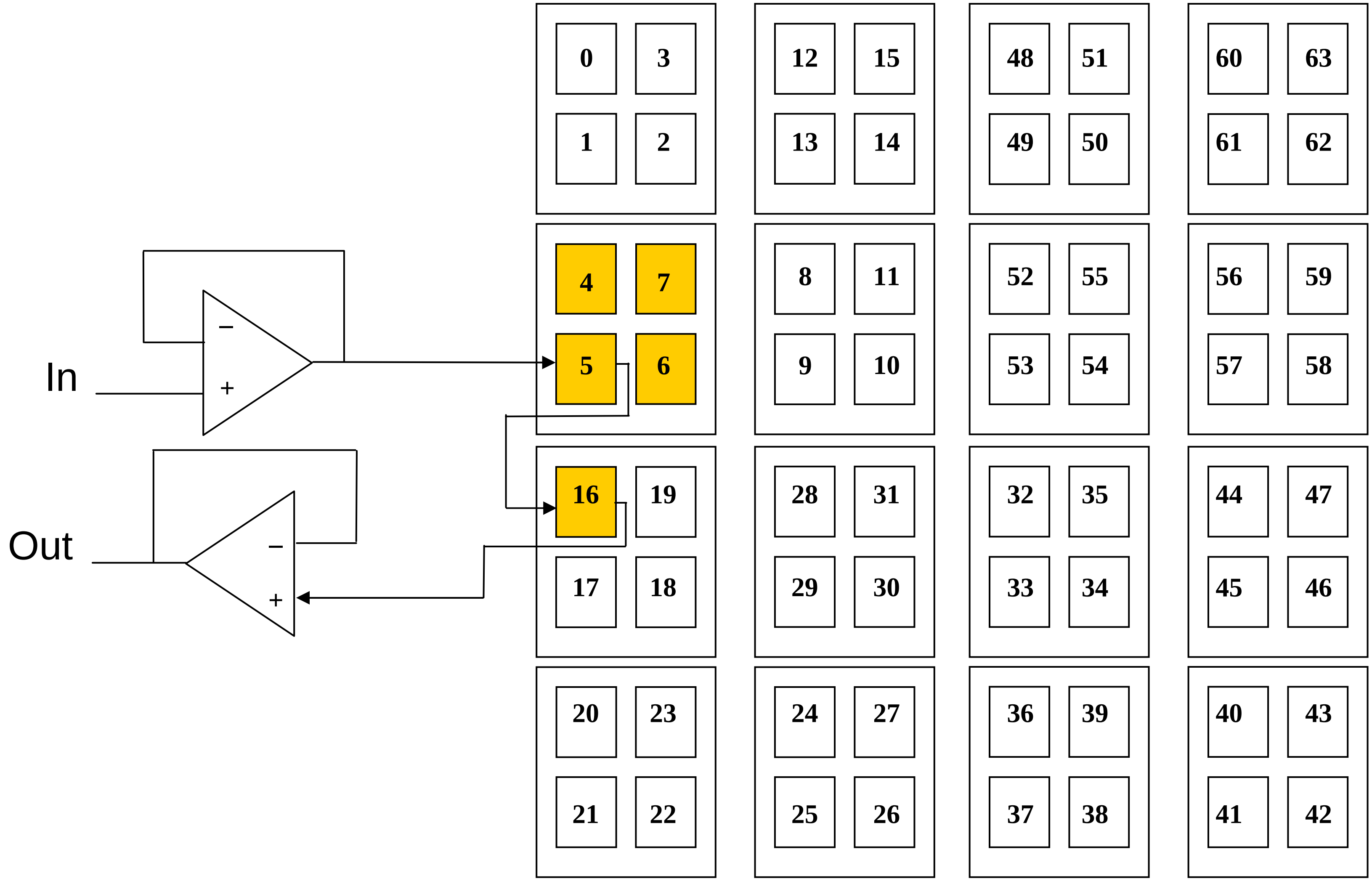
- ⇨ Use open-loop input-output data from the plant.
- ⇨ Excitation signals are selected to excite the salient dynamic response of the plant.
- ⇨ An added sine stimulus and a sine sweep stimulus are a good means of providing the input frequency content needed.

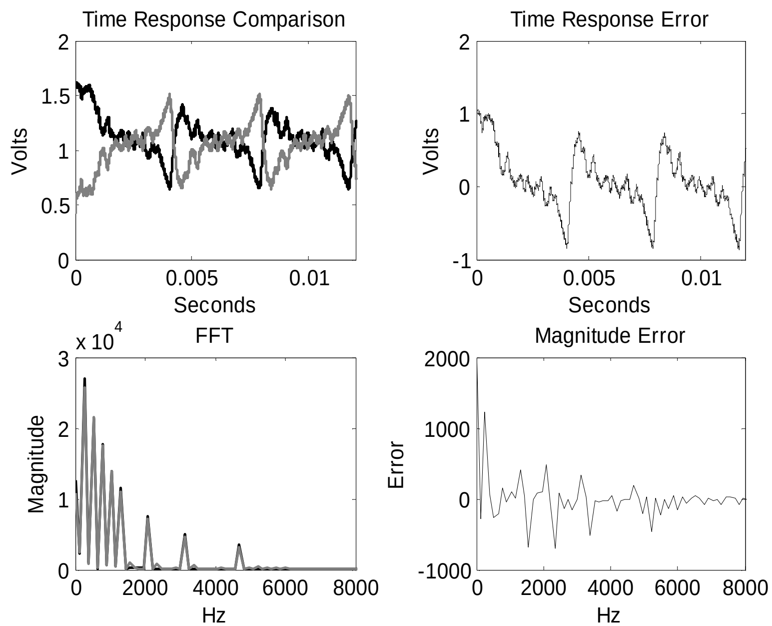


- ⇨ Performing evolution in stages was found to profitable in this work
  - → One type of sine stimulus has advantage over the other at different phases in the evolution of the plant transfer function.

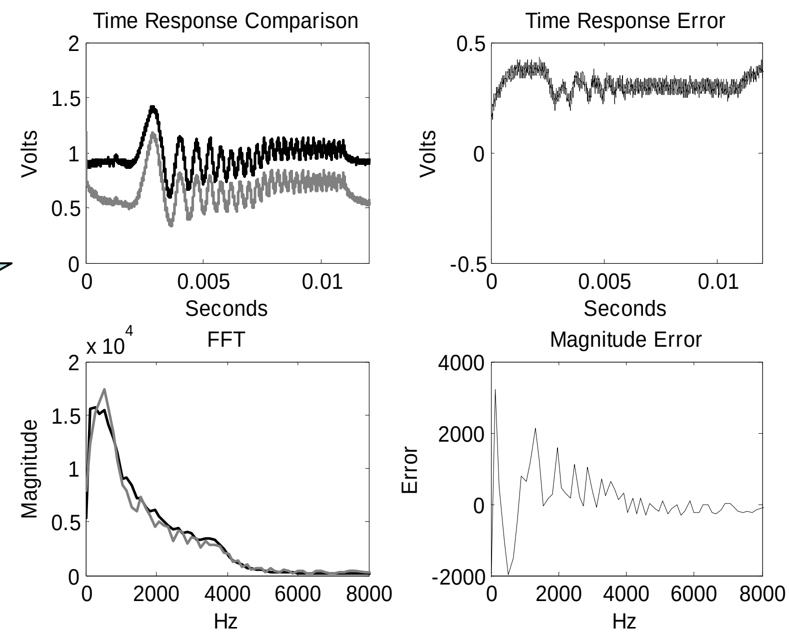
Physical Configuration for Forward TF



First Stage Results



Invert Output



Evolution using

1. added sine input
2. Fitness based on FFT magnitude and time response mean error

$$F = \left| \frac{P}{n} \sum_{i=1}^{n} Etime_i \right| + \left| \sum_{j=1}^{k} M_j * Emag_j \right|$$

3. Converged at 18,000 generations

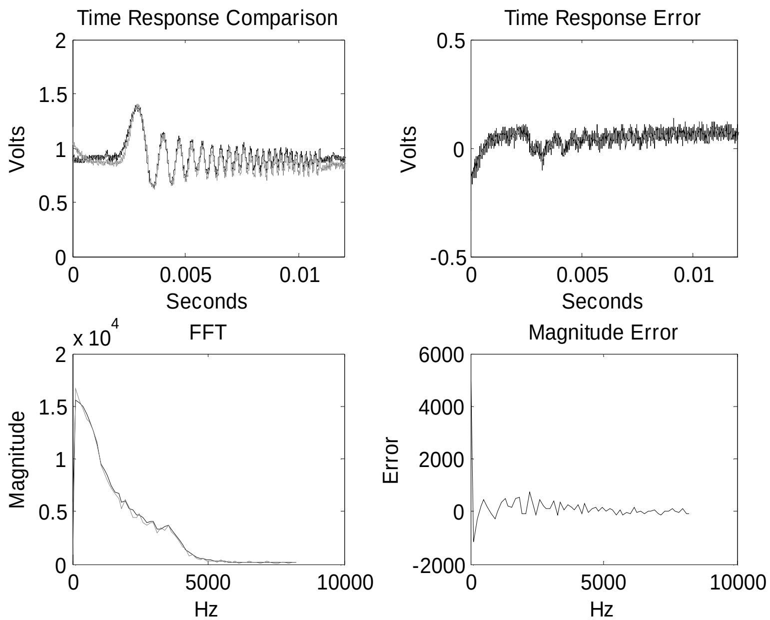
Prep for second stage evolution includes

1. Inverting output
2. Sine sweep input

Plant response in black
FPTA response in gray

Second Stage and Control Results

Evolved Model



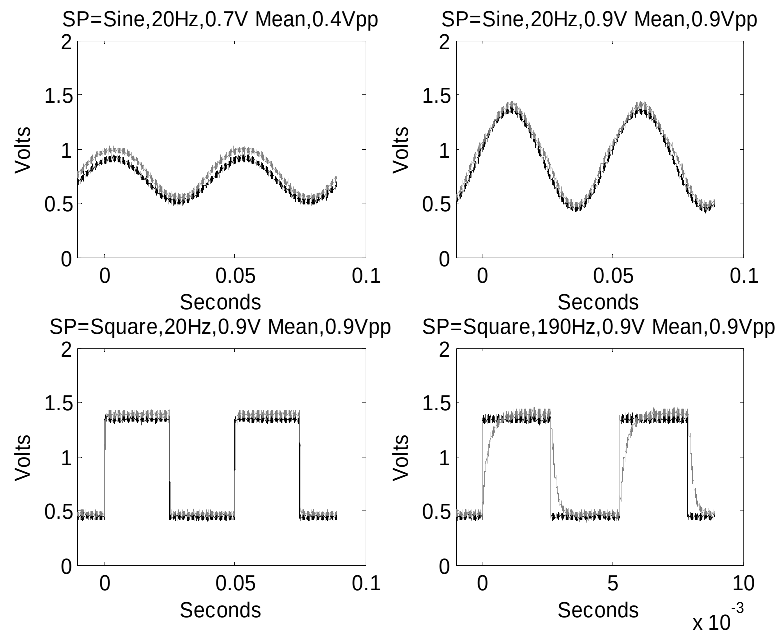
Evolution using

1. Sine sweep
2. Fitness based on FFT magnitude and time response error

$$F = \sum_{i=1}^{n}\left|Q_i * Etime_i\right| + \left|\frac{P}{n}\sum_{i=1}^{n} Etime_i\right| + \left|\sum_{j=1}^{k} M_j * Emag_j\right|$$

3. Converged at 3,500 generations

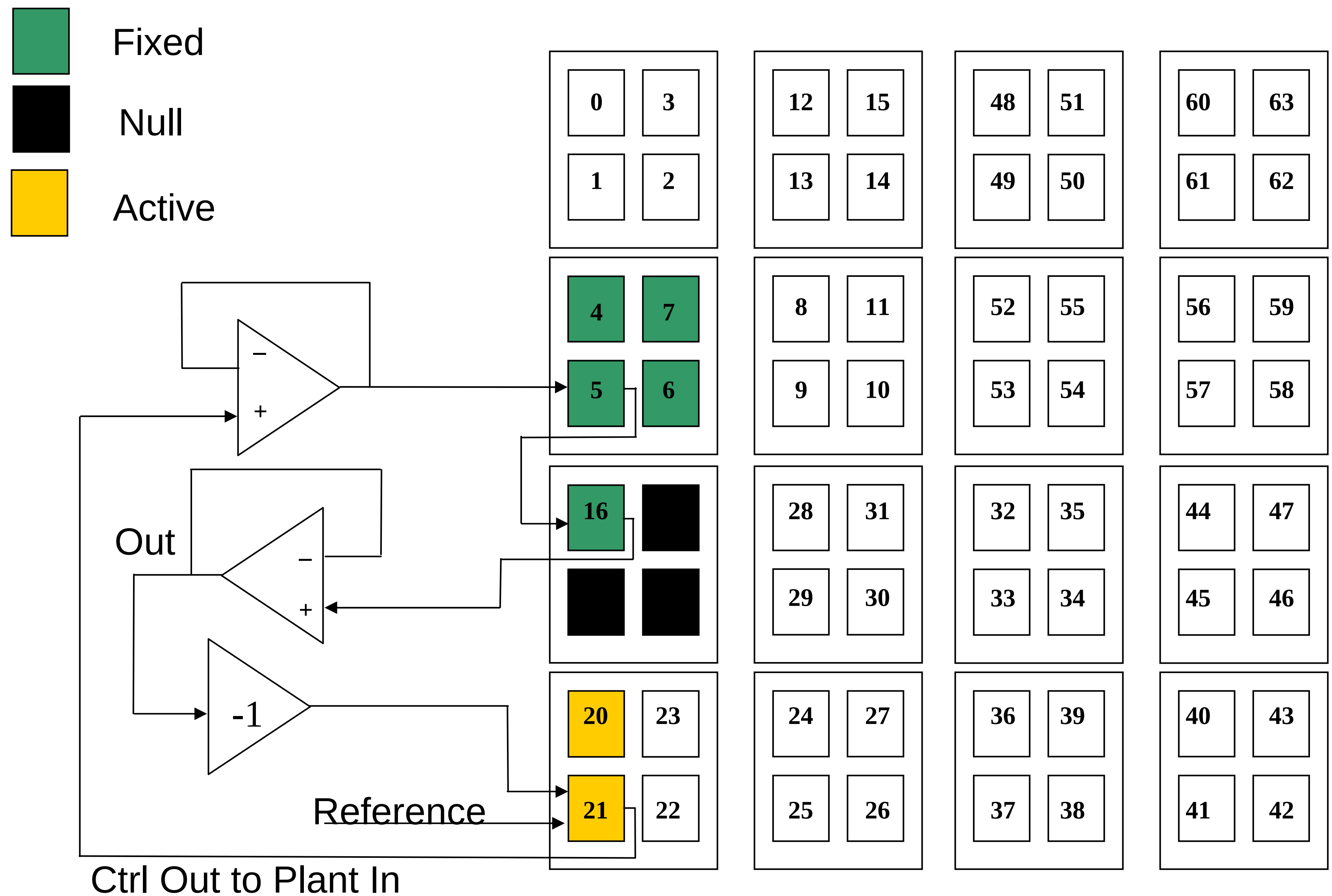
Evolved Controller



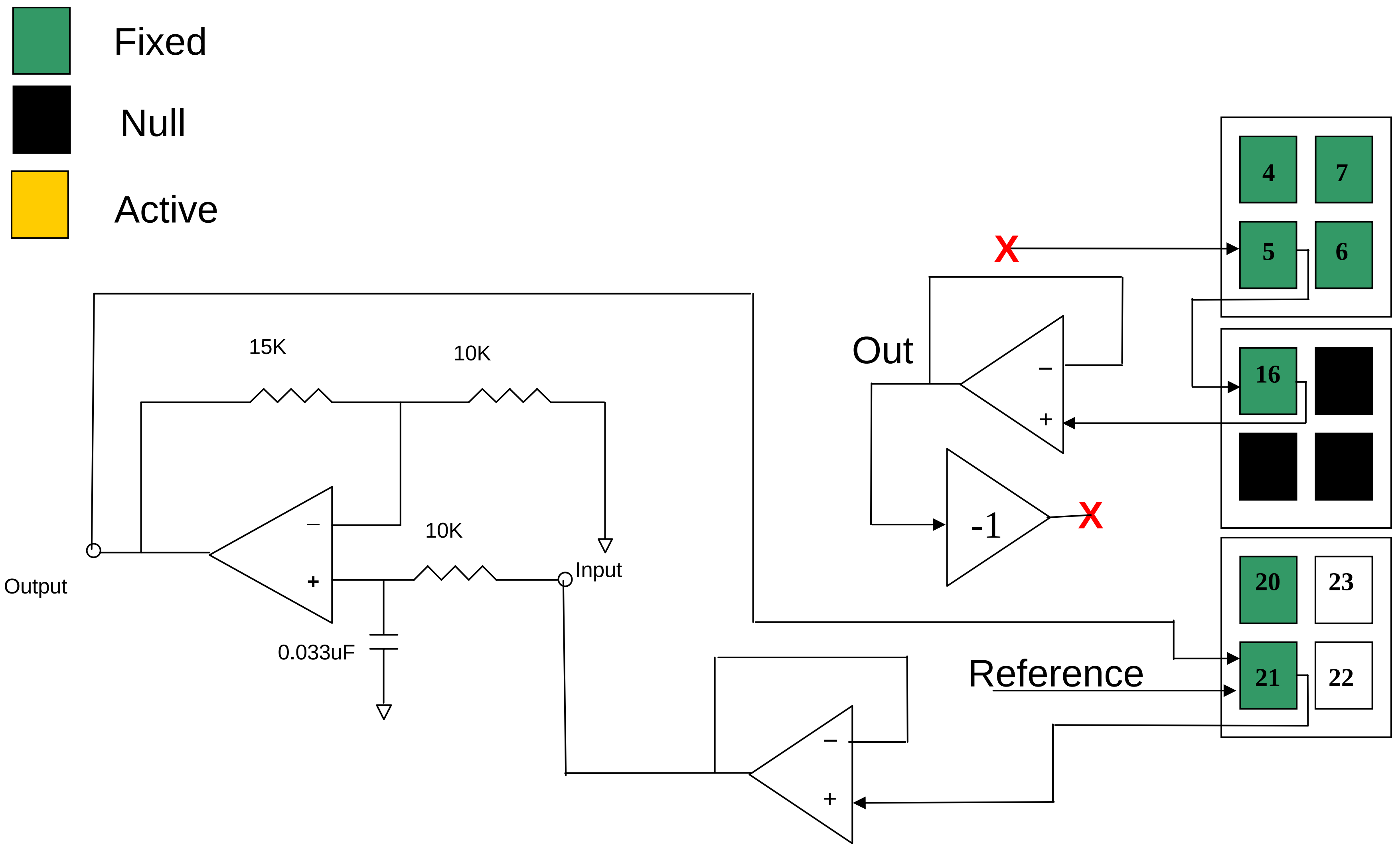
Time response plots for control of the simulated analog plant using the evolved controller (104 generations)

Reference command in black
EAC controlled plant response in gray

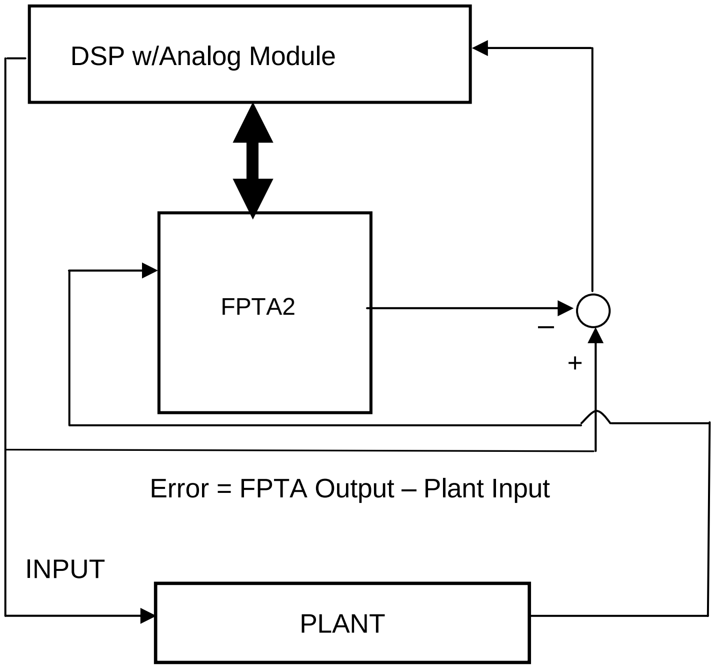
Physical Configuration for Controller Evolution



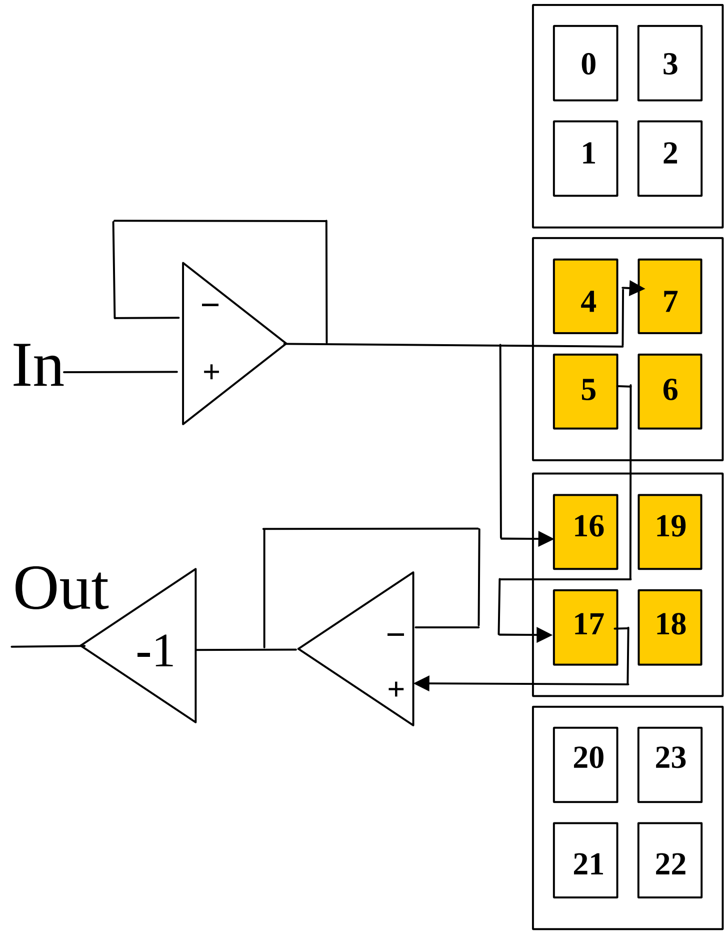
Configuration for Control of Plant



Evolving Inverse TFs



Experimental hardware configuration



Cell physical configuration for evolution of inverse transfer function

2nd and 3rd Stage Inverse TF Results

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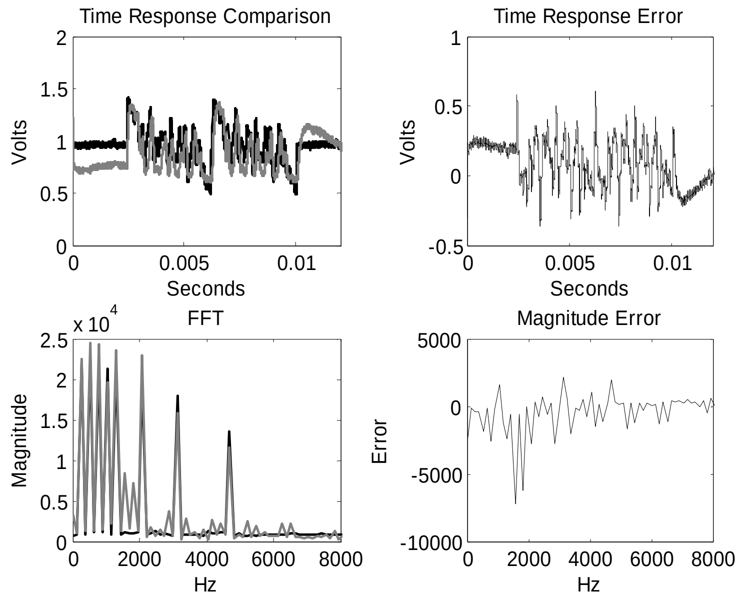
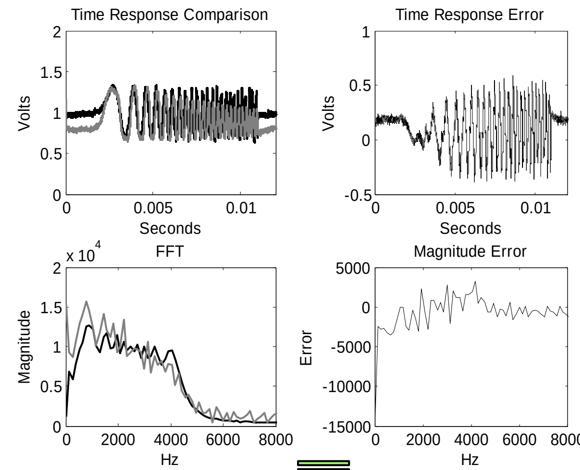
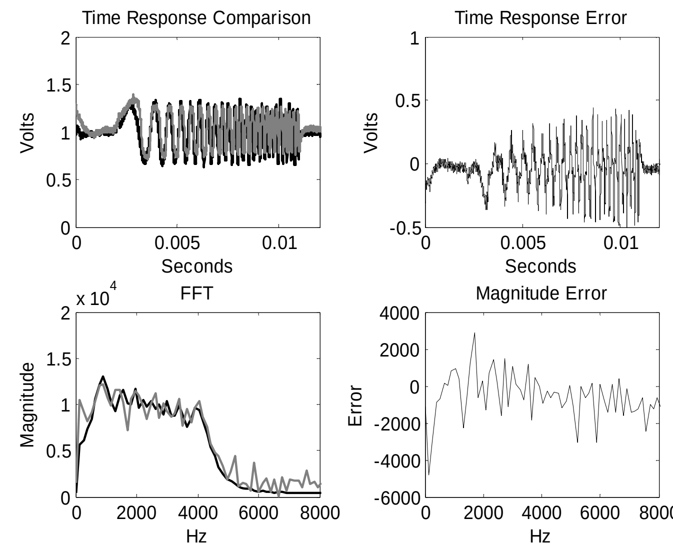
2nd Stage Evolved Inverse Model





3rd Stage Evolved Inverse Model



Evolution using

1. Added Sine and Sine sweep
2. Fitness based on FFT magnitude and time response error
3. 2nd Stage Converged at 17,000 generations
4. 3rd Stage converged at 23,600 generations

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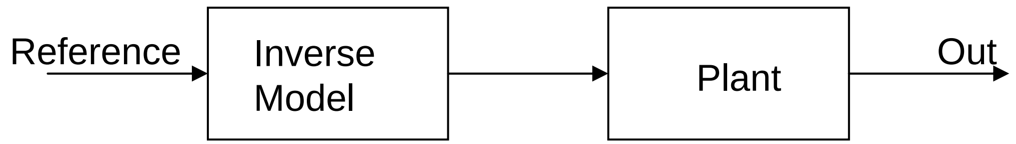
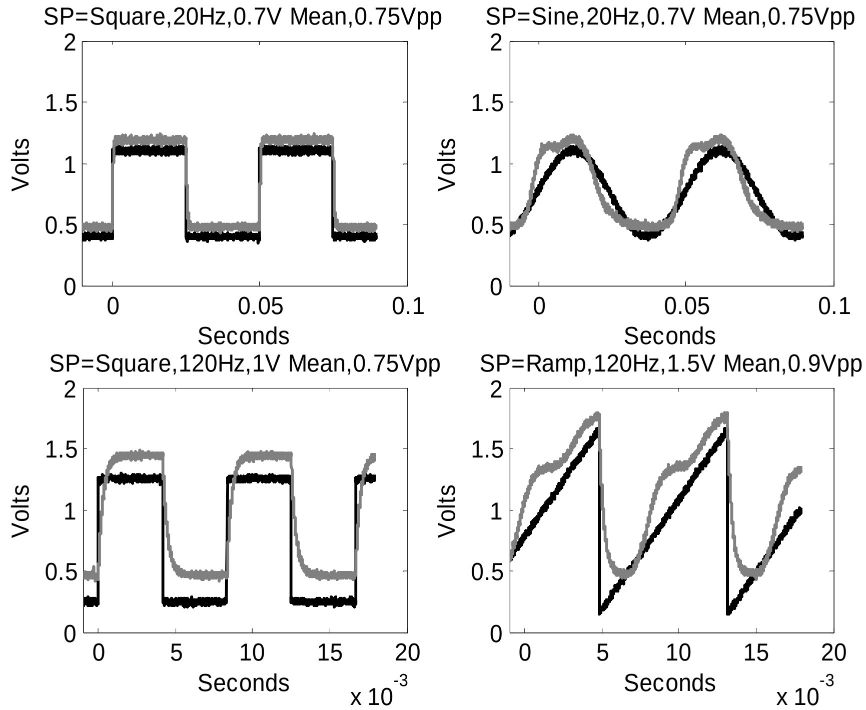
Inverse Control

- The evolved inverse transfer function was directly applied to the control of the analog plant
- Does not match precisely
  - → More work to do!
- In practice, the inverse model will be used as a feed forward control component along with a simple feedback controller.



Experimental configuration for direct inverse control



Time response plots for direct inverse control of the analog plant

Summary

- Protecting the controlled plant from the evaluation of poor individuals can be addressed by evolving transfer functions and controllers using the EAC architecture presented.
- Intrinsic evolution requires no analytical knowledge and can be used to autonomously identify plant transfer functions in reconfigurable hardware.
  - Computer simulation approaches exist for dynamic systems, but generally require extensive computing capability, and may require significant a-priori analysis by a human designer.
  - In a remote system, such as a spacecraft, neither a human designer nor extensive computing resources are available.
  - Hardware implementation offers real-time response and the possibility for a high degree of parallelism.
- Transfer functions could be evolved to represent un-expected dynamics and possibly non-linearities due to failures that arise in a plant
  - While not shown here, the evolution process using the FPTA has a preference for non-linear responses

Future Work

- The transfer function should be continuously updated to track changes in the plant during normal operation.
  - EAC will be prepared to modify the controller quickly, when the need arises.
- EAC must be proven with more complex plant dynamics.
- Future research funded by NASA NRA
  - Autonomous EAC controlling more complex plant dynamics
  - Including domain knowledge in the evolutionary algorithm
  - Design of an evolution oriented reconfigurable device specifically targeted for control applications.
    - FPTA2 represents a significant innovation in evolution oriented reconfigurable electronics, but not designed for analog simulation and control applications.